中国科学院大学
University of Chinese Academy of Sciences

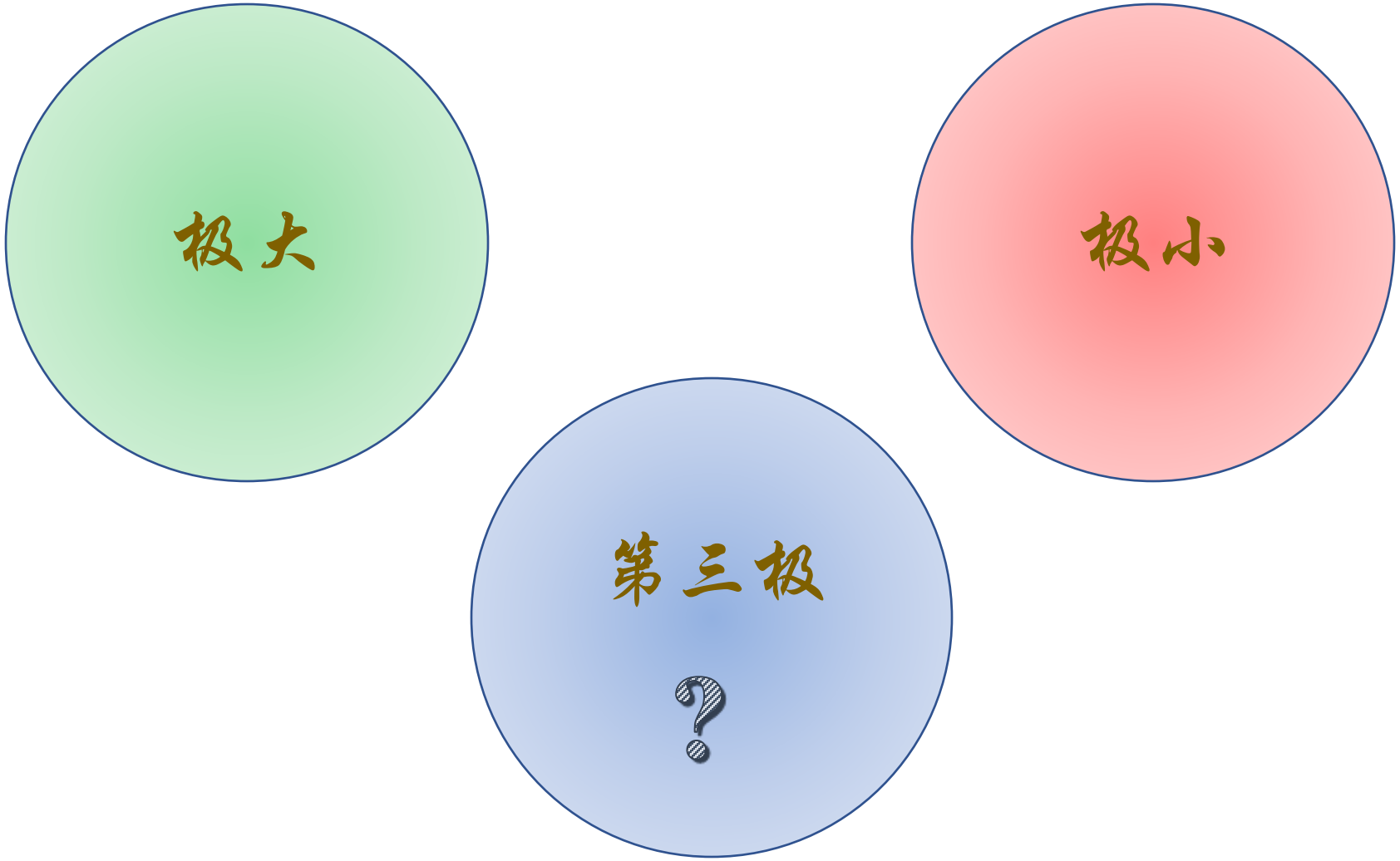
通往理论物理世界第三极

-- 软物质物理简介

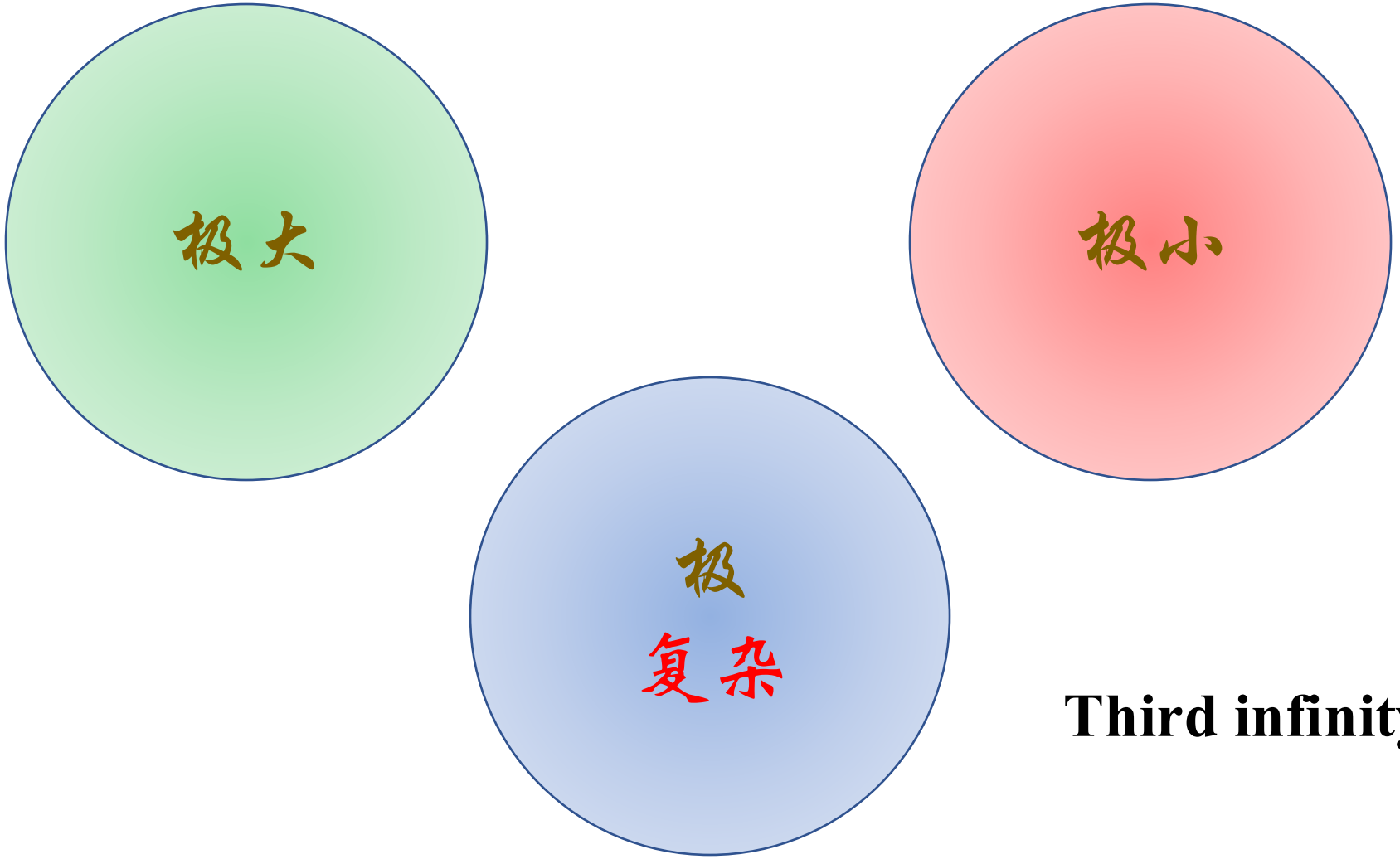
孟凡龙

中国科学院理论物理研究所

物理研究的对象：三极



物理研究的对象：三极



Third infinity

还原论不能处理极复杂问题么？

1滴水的数据存储要占据多少空间

- 1滴水～10＾21水分子
- 假设1个水分子的数据占据1个比特（实际不只1个），那么需要～10＾21 /(10＾12) ~10＾9个1TB的硬盘存储
- 10＾9*0.1*0.03/10＾4～100个足球场（1瓶水～100个海淀区）

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- 1滴水～10^21水分子
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- 10^9*0.1*0.03/10^4～100个足球场（1瓶水～100个海淀区）

自由度太高又伴随多体相互作用和时空演化

第三极：无限复杂（复杂系统）

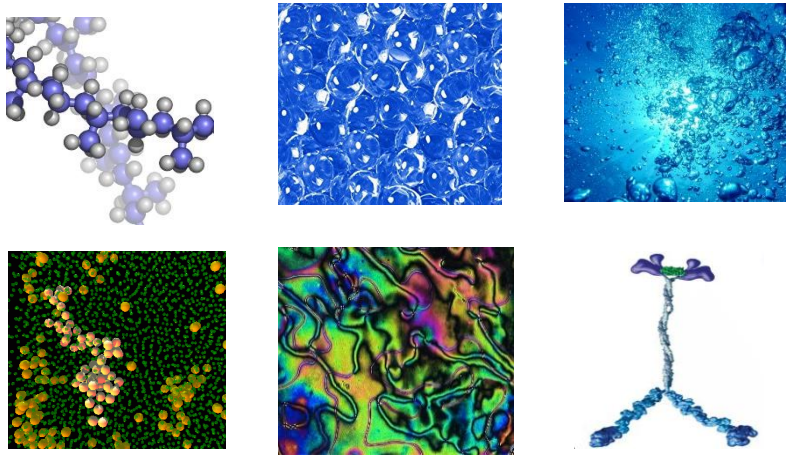
Infinitely complex

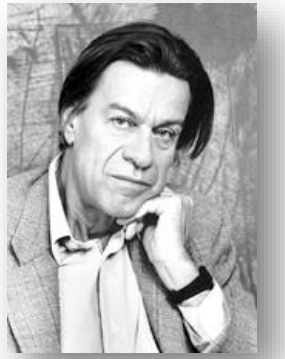
SOFT MATTER PHYSICS, BIOPHYSICS

…

软物质：1991年由de Gennes提出

例如：高分子，凝胶，液体，胶体颗粒，液晶，生物材料等等





Pierre-Gilles de Gennes
1991年诺贝尔物理学奖

现实场景一：软物质涵盖天然材料和大部分生物质

天然橡胶

纤维素

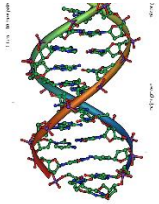
淀粉

蜘蛛丝/蚕丝

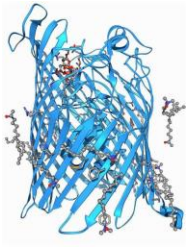
甲壳素

现实场景二：软物质是生命体系的物质基础

1 nm	10 nm	100 nm	500 nm	1000 nm

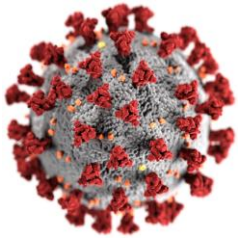


DNA, RNA

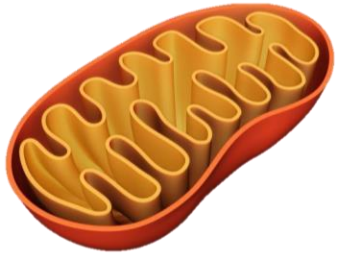


蛋白

细胞膜（厚度）

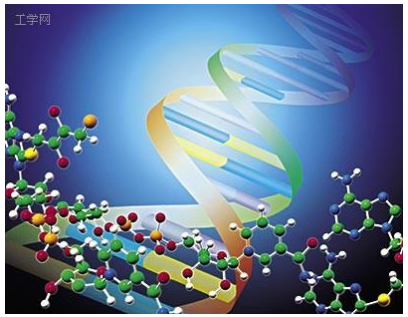


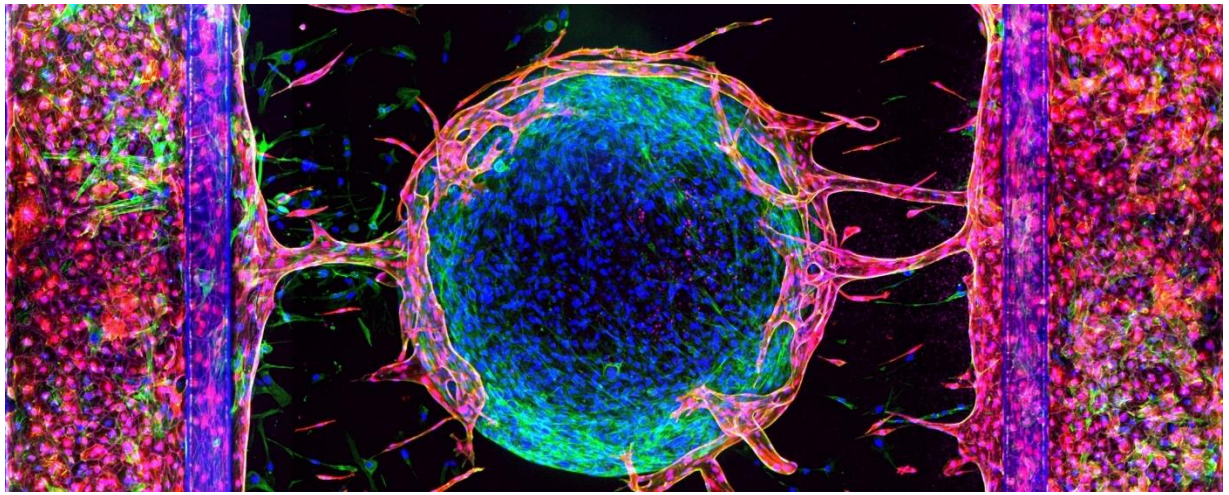
病毒



细胞器

细胞





现实场景三：软物质覆盖几乎所有的合成材料

软物质的基础研究需要多学科共同努力

社会需要

工业　农业　国防　能源　健康　安全　环境

满足

技术开发

生命

材料

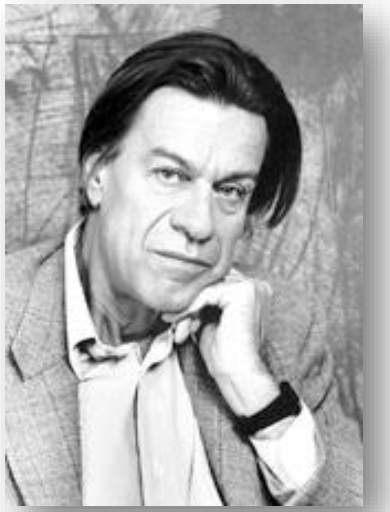
支撑

基础研究

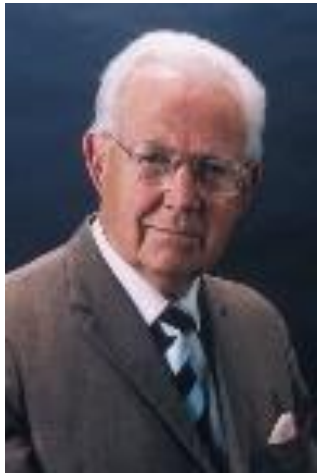
化学　物理　数学

Soft matter physics: interesting or not

世界著名软物质物理学家



Pierre-Gilles de Gennes
1991诺贝尔物理学奖



Sam F. Edwards
Cavendish Professor

Giorgio Parisi
2021诺贝尔物理学奖

Mike Cates
Lucasian Professor

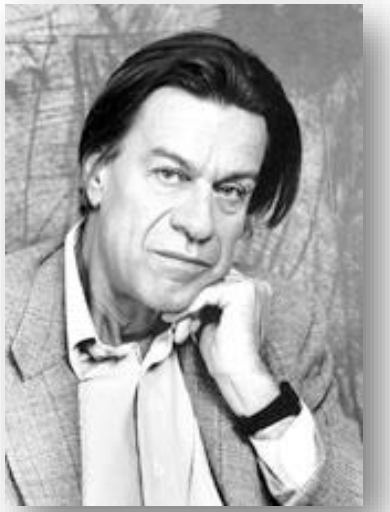
…

Cavendish Professor

物理:

- James Clerk Maxwell (1871–1879)
- Lord Rayleigh (1879–1884)
- J. J. Thomson (1884–1919)
- Ernest Rutherford (1919–1937)
- William Lawrence Bragg (1938–1953)
- Nevill Francis Mott (1954–1971)
- Brian Pippard (1971–1984)
- Sam Edwards (1984–1995)
- Richard Friend (1995–present)

世界著名软物质物理学家



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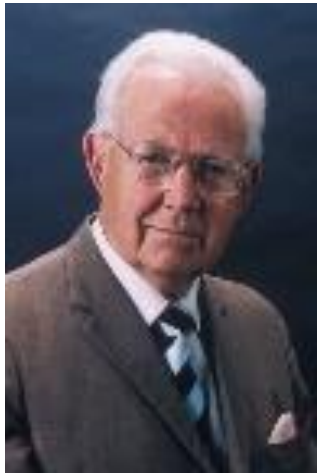

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Lucasian Professor

应用数学和理论物理

Lucasian Professor

应用数学和理论物理

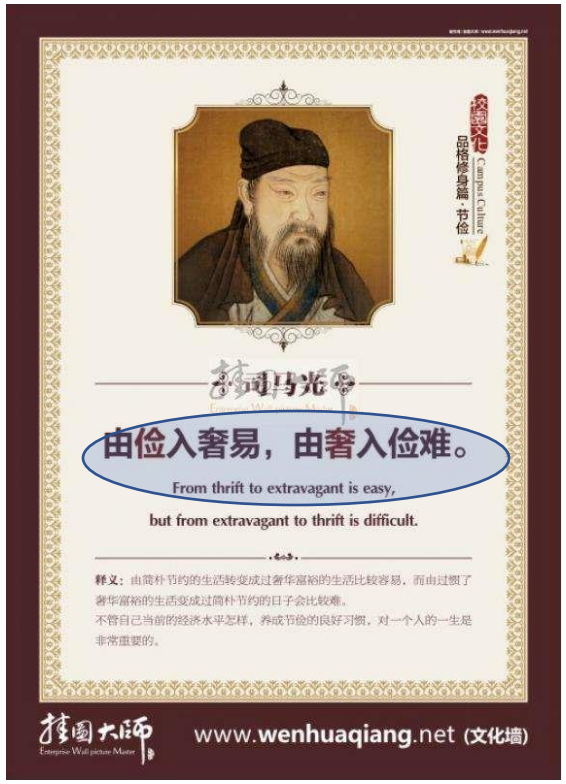
1663		Isaac Barrow (1630–1677)	Classics and mathematics	6
1669		Isaac Newton (1643–1727)	Mathematics and physics	33
1702		William Whiston (1667–1752)	Mathematics	9
1711		Nicholas Saunderson (1682–1739)	Mathematics	28
1739		John Colson (1680–1760)	Mathematics	21
1760		Edward Waring (1736–1798)	Mathematics	38

1798	Isaac-Milner.gif	Isaac Milner (1750–1820)	Mathematics and chemistry	22
1820		Robert Woodhouse (1773–1827)	Mathematics	2
1822		Thomas Turton (1780–1864)	Mathematics	4
1826		George Biddell Airy (1801–1892)	Astronomy	2
1828		Charles Babbage (1791–1871)	Mathematics and computing	11
1839		Joshua King (1798–1857)	Mathematics	10

1849		George Gabriel Stokes (1819–1903)	Physics and fluid mechanics	54
1903		Joseph Larmor (1857–1942)	Physics	29
1932		Paul Dirac (1902–1984)	Physics	37
1969		James Lighthill (1924–1998)	Fluid mechanics	10
1979		Stephen Hawking (1942–2018)	Theoretical physics and cosmology	30
2009		Michael Green (born 1946)	String theory	6
2015		Michael Cates (born 1961)	Statistical mechanics of soft condensed matter	current

软物质物理做的是什么

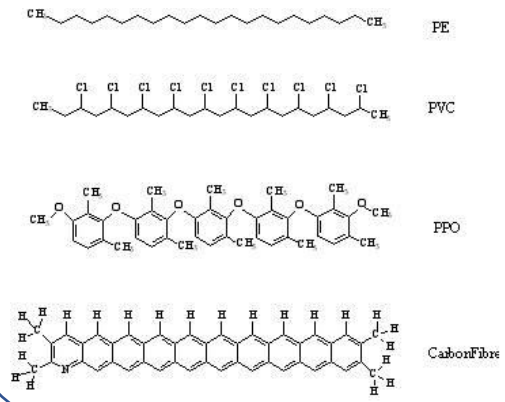
软物质物理

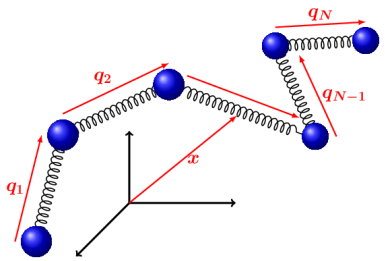


软物质物理：由繁(complexity) 入简(simplicity)

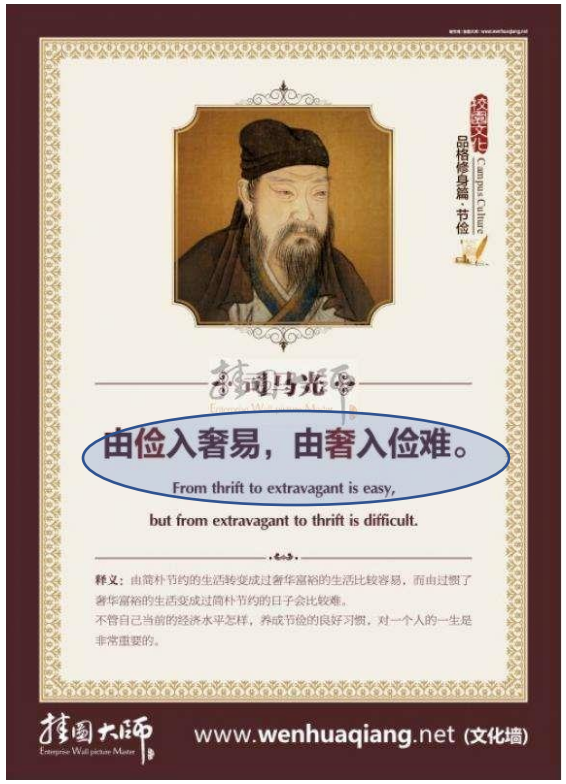
一个例子：高分子

聚乙烯、聚丙烯、聚氯乙烯、聚苯乙烯、聚甲醛、聚碳酸酯、聚砜、聚酰亚胺、聚芳醚、聚芳酰胺...





软物质物理

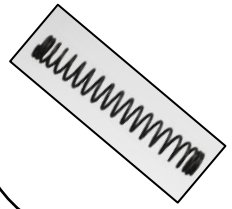


软物质物理：由繁(complexity) 入简(simplicity)

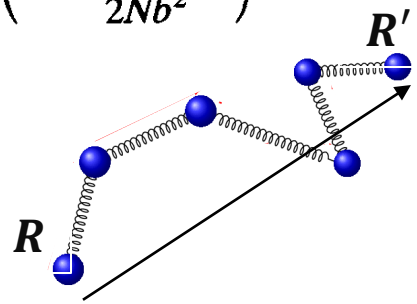
一个例子：高分子

$$\left(\frac{\partial}{\partial N}-\frac{b^2}{6}\frac{\partial^2}{\partial \boldsymbol{R}^2}+\frac{1}{k_B T}U_e(\boldsymbol{R})\right)G(\boldsymbol{R},\boldsymbol{R}';N)=\delta(\boldsymbol{R}-\boldsymbol{R}')\,\delta(N)$$

$$G(\boldsymbol{R}-\boldsymbol{R}';N)=\left(\frac{2\pi N b^2}{3}\right)^{-3/2}\exp\left(-\frac{3(\boldsymbol{R}-\boldsymbol{R}')^2}{2Nb^2}\right)$$



自由能：$F\sim\frac{k_B T}{Nb^2}(\boldsymbol{R}-\boldsymbol{R}')^2$



软物质物理研究的理论方法

经典力学

电动力学

量子力学

统计力学（物理）

⇩

非平衡态统计物理

孟凡龙 课题组（软物质理论和统计物理）

当前研究兴趣：

通过构建解析理论和发展数值工具研究：

1. 远离平衡态--活性物质系统集体动力学模式；
2. 非平衡态高分子系统的统计物理理论；
3. 多组分溶液系统在复杂环境中的相分离模型；

…

Recent publications:

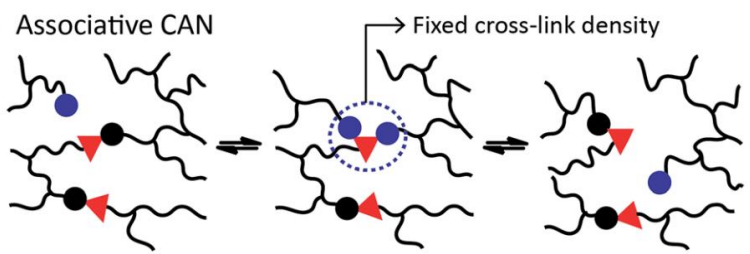
Physical Review Letters 132, 204002 (2024);
Physical Review Letters 131, 068101 (2023);
Physical Review Letters 131, 158301 (2023);
Nature Communications 13, 5753 (2022);
Physical Review X, 11, 031065 (2021);
PNAS 118, e2102828118 (2021);
Physical Review Letters 126, 078001 (2021);
Physical Review Letters 125, 268001 (2020);
Nature Communications 10, 4696 (2019);
Nature Communications 10, 2444 (2019);
Physical Review Letters 120, 188101 (2018)
…

Meng Group Website:
http://lib.itp.ac.cn/html/meng/

代表性工作一：动态交连网络的统计物理理论

研究背景

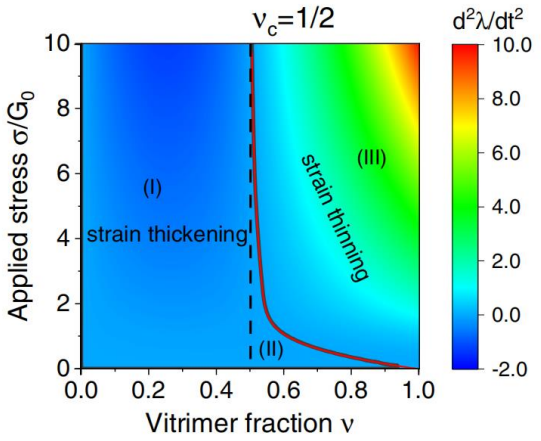
动态交连网络是一种**革新型高分子材料**，其中，**“类玻璃化弹性体的制备和性质研究”**入选2021年12月由中国科学院科技战略咨询研究院、中国科学院文献情报中心与科睿唯安(Clarivate)联合发布的《研究前沿》报告中的**新兴前沿**。



研究成果

从动态交连键的微观动力学方程出发，构造**动态交连网络**（包括类玻璃化弹性体、键交换型液晶弹性体等）的**含时统计物理理论（无人区）**

$$F(t) = F_{\mathrm{pe.n.}}(t;0)e^{-\beta t} + \int_0^t \mathrm{d}t'\beta e^{-\beta(t-t')}F_{\mathrm{pe.n.}}(t;t')$$

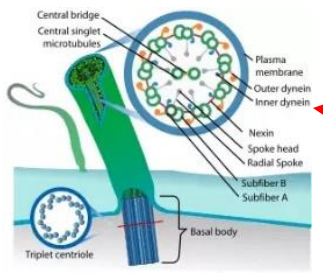


FM, Saed, Terentjev, Nat. Commun. 13, 5753 (2022) 类玻璃化弹性体

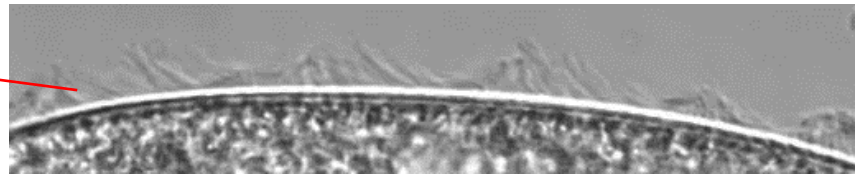
Zhao, **FM**, Phys. Rev. Lett. 131, 068101 (2023) 键交换型液晶弹性体

代表性工作二：纤毛/鞭毛的动力学模型

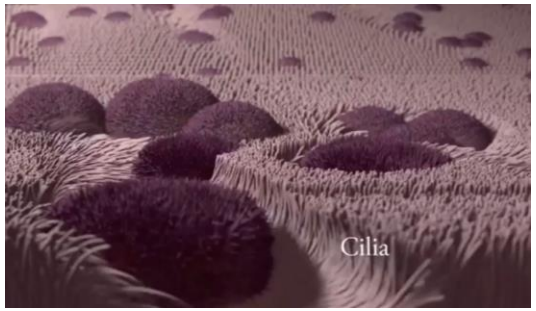
研究背景



纤毛示意图



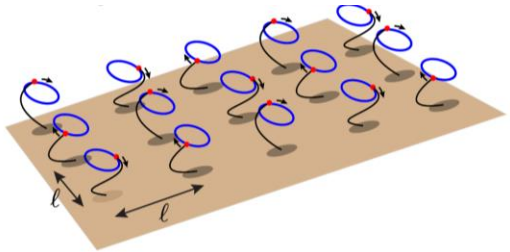
异时波集体动力学模式

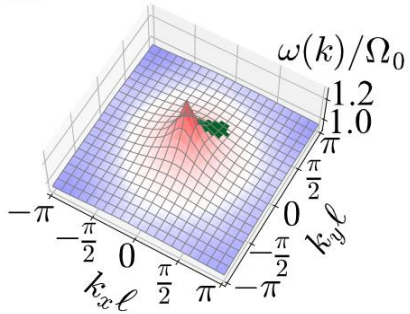


流体输运、微生物游动等功能

- 微尺度纤毛集体波式摆动

$$\frac{d\phi_i}{dt} = \frac{f(\phi_i)}{\zeta(\phi_i)a} + \frac{1}{a}\sum_j \boldsymbol{t}_i(\phi_i)\cdot\boldsymbol{G}(\boldsymbol{R}_i,\boldsymbol{R}_j)\cdot\boldsymbol{t}_j(\phi_j)f(\phi_j)$$

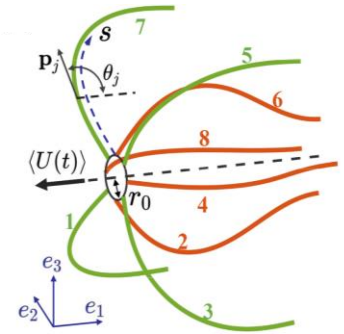


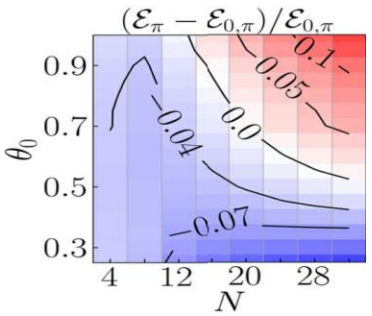


FM, et al., PNAS 118, e2102828118 (2021)

- 多鞭毛微生物的物理模型

$$8\pi\mu(\partial_t \mathbf{r}_j - \mathbf{v}_j) = \Lambda[\mathbf{f}_j] + K[\mathbf{f}_j]$$





Hu, **FM**, Phys. Rev. Lett. 132, 204002 (2024)

代表性工作三：微观游泳体的集体动力学理论

研究背景

自Vicsek模型提出后，大量研究发现非平衡系统能够涌现出新奇的物理现象，比如活性的引入可以打破 Mermin—Wagner 定理（2020年Onsager Prize）。**虽然这方面理论研究开始起步，但是现有模型过于唯象，缺少微观物理基础。**

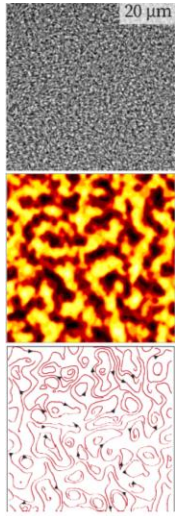
Vicsek

Toner

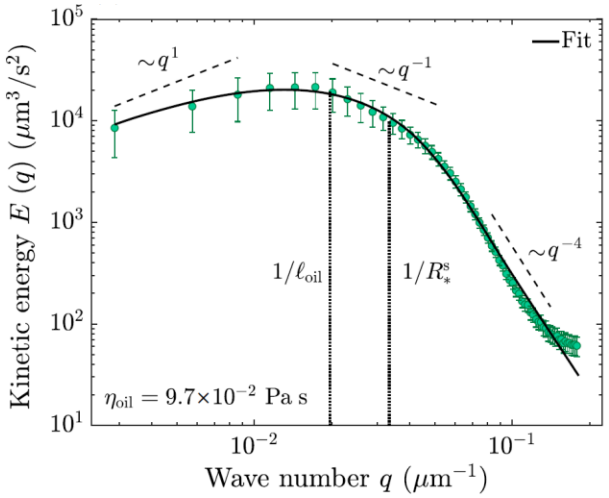
Tu

美国物理学会 Onsager Prize（2020）

- 活性湍流涌现



湍流能谱

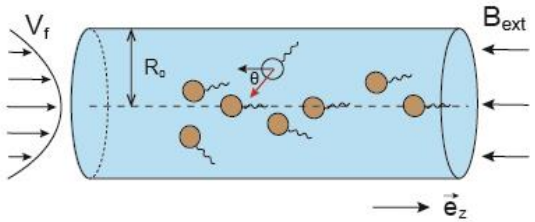


Martnez-Prat, et al., Phys. Rev. X 11, 031065 (2021)
Wei, et al., Adv. Sci. 11, 2402643 (2024)

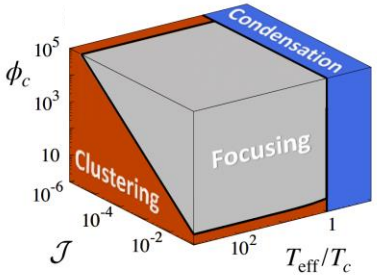
- 磁性游泳体动态斑图涌现

$$\frac{d\boldsymbol{n}}{dt} = \left[\frac{m_0\boldsymbol{n}\times(\boldsymbol{B}_{\rm ext}+\boldsymbol{B}_{\rm int})}{\zeta_R} + \frac{\nabla\times\boldsymbol{V}_{\rm f}}{2} + \boldsymbol{\xi}_R\right]\times\boldsymbol{n}$$

$$\frac{d\boldsymbol{r}}{dt} = v_0\boldsymbol{n} + \boldsymbol{V}_{\rm f} + \frac{1}{\zeta}\nabla(m_0\boldsymbol{n}\cdot\boldsymbol{B}_{\rm int}) + \boldsymbol{\xi}$$



磁性微观游泳体动力学方程



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谢谢

Meng Group Website:
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